Paper to be published at the IEE Conference, Reliability of Transmission & Distribution Networks, London, February 2005

WIND TURBINE RELIABILITY, HOW DOES IT COMPARE WITH OTHER EMBEDDED GENERATION SOURCES

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Key Words: Wind Turbine, Reliability, Networks, Homogeneous Poisson Process, Repairable Systems

Abstract

Wind turbines are being introduced into the distribution and transmission networks of Europe in increasing numbers. Their reliability has become a factor in network reliability. This has been exemplified by a report from Germany about the reserve necessary to maintain a secure supply with high levels of wind-powered generation in the system. Some difficulty arises because of the variable nature of the wind resource but some is attributable to the unreliability of wind turbines as power sources.

This paper surveys the reliability of wind turbines in Denmark and Germany using data collected from Windstats over the past 7 years. The survey shows that turbines in Germany appear less reliable than turbines in Denmark. The reason for the difference is the greater number of newer, larger turbines being introduced in Germany, which increase Failure Rates because of Early Failures.

The authors intend to use the data extracted from this survey to predict the reliability of large wind turbines placed in more inclement positions in the network, for example offshore.

1. Introduction

An increasing number of wind turbine generators are being incorporated into networks. They are a key part of the distribution network and as such affect the overall system reliability. The configuration, technology and size of wind turbines have been changing rapidly over the last few years. Larger turbines, >2MW, are being installed onshore and offshore throughout Europe. The potential for more wind turbines to be erected in remote locations and offshore is increasing the need to provide accurate reliability predictions so that network reliability calculations can be done and wind turbine life and maintenance predicted. Some wind turbine operators are also concerned about the contribution which wind energy makes [1] and reliability is part of that debate. This paper takes recorded failure data from Windstats records to analyse the reliability of German and Danish wind turbine data.

2. Windstats Data

Windstats [2] is a database recording details of operation of wind turbines in many countries. The overall period investigated by the paper was October 1996 to September 2003. This period was selected to ensure that the data being considered concerned only modern designs of wind turbines. Data from two countries in particular have been analysed, Germany and Denmark. This was done because the wind turbine population for these two countries is large. The data is published each quarter but information is available at monthly intervals from Denmark and at quarterly intervals from Germany. Windstats gives information about the items shown in Table I for turbines reporting to the Survey.

Information	Unit
Length of Reporting Interval	Month or quarter
Turbines reporting in population	Number N per Interval, i
Turbines added and removed from the population	Number per Interval
Total rating of all turbines in population	kW
Energy produced by all turbines in population	kWh in Interval
Failures in major subassemblies	Number, n_i per Interval, i, per Subassembly, see Table II
Time lost due to Subassembly Failures	Hours, T_s
Time lost due to Non-Subassembly Failures	Hours, T_n
Time lost due to Failures for which only hours recorded	Hours, T_h
Total time lost	Hours, $T_t = T_s + T_n + T_h$

Table I, Data recorded in Windstats for the two Populations.

A wind turbine is made up of a number of key subassemblies and Windstats provides failure information for each subassembly for each Interval, as set out in Table II. German and Danish data have slight variations in the name used for each subassembly and the Table shows the name used in this paper and that from each of the two National Populations. From the data a Failure Rate/Subassembly/Turbine/Year, λ_k, for the *kth* Subassembly has been obtained for each Population at each Interval, i, in the Overall Period. This has been done by dividing the Number of Subassembly Failures, n_i, by the Number of Turbines, N, in the Population for the Interval being considered and correcting for the number of hours in the Interval compared to the number of hours in a Year as follows:

$$\lambda_k = \frac{\sum_{i=1}^{k} n_i}{N \sum_{i=1}^{k} T_i} \times 8760 \qquad (1)$$

An average Failure Rate per Turbine per Year for each Interval has also been obtained by summing all the Subassembly Failure Rates for that Interval. Figure 1 shows the variations in these values in the Overall Period.

Subassembly Name used in this Paper	**Subassembly Name used in Germany**	**Subassembly Name used in Denmark**
Rotor Blades	Rotor	Blades, Hub
Air Brake	Air Brake	Air Brakes
Mechanical Brake	Mechanical Brake	Mechanical Brake
Main Shaft	Main Shaft	Main Shaft, Coupling
Gearbox	Gearbox	Gearbox
Generator	Generator	Generator
Yaw System	Yaw System	Yaw System
Electrical Controls	Electrical Controls	Electrical Control
Hydraulics	Hydraulics	Hydraulic System
Electrical System	Electrical System	Electrical Control
Mechanical or Pitch Control	Mechanical Control	Pitch Control
Other	Other, Instrumentation, Sensor, Windvane	Other

Table II, Wind Turbine Subassemblies in the two Populations.

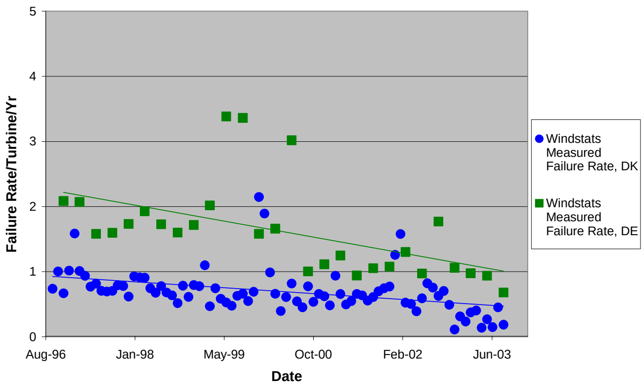

Figure 1, Average Failure Rates of German and Danish Wind Turbines calculated from Windstats data.

The results of this analysis are striking:

- Failure Rates in both populations are falling with time.
- German Failure Rates are higher than Danish Failure Rates.
- Danish Failure Rates, obtained monthly, exhibit some periodicity.
- There are some significant high Failure Rates in both populations and some of these coincide in time.

Some of these results are confirmed by a report from DOWEC [3].

3. Machinery Life & Reliability

The train of equipment at the heart of a modern, variable speed wind turbine includes the key subassemblies shown in Table II. This paper intends to use turbine and subassembly reliability results, plus a mathematical life model to develop a reliability model for large, modern, wind turbine configurations. The work is based upon one of the author's experience predicting the life of electrical machines used in a power system [4].

From an engineering point of view subassemblies, and therefore the turbine, are repairable. The Power Law Process (PLP) is commonly used in the reliability analysis of complex repairable equipment, its intensity function describes the failure rate, λ, of a piece of machinery, such as a wind turbine, and has the form:

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \qquad (2)$$

β is a coefficient, θ has dimensions of time and $\theta > 0$; $t \geq 0$. Figure 2 shows a complete Life Curve described by Equation 1 and this is usually referred to as the bathtub curve. The 3 regions of the Life Curve can be seen:

- Early Failures, $\beta < 1$
- Constant Failure Rate, $\beta = 1$
- Deterioration, $\beta > 1$

When $\beta = 1$, Equation 1 reduces to the Homogeneous Poisson Process (HPP) and θ becomes the Mean Time Between Failure, MTBF, of the machine where:

$$\theta = \frac{1}{\lambda} = \frac{\sum_{i=1}^{k} T_i}{\sum_{i=1}^{k} n_i} \quad hrs \qquad (3)$$

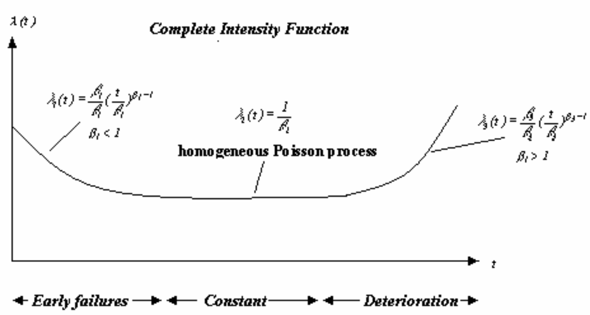

Figure 2, The Life Curve of machinery.

If we collect data from a large number of turbines, the average Failure Rate at a given Interval, as calculated in Section 1 and displayed in Figure 1, could be assumed to be the Failure Rate of a single, average turbine. This assumption would imply that every turbine was on the Constant Failure Rate part of the Life Curve, ie the HPP region. But the Failure

Rate is an average over a Population of 900-4000 turbines, each of which has a different technology and age, and may not necessarily lie on the flat part of the Life Curve. In order to select a valid mathematical model, the Windstats data must analysed further to determine the characteristics of the German and Danish Populations.

4. Further Analysis of Windstats Data

Figure 3 shows that the German population of reporting turbines is much larger than the Danish and is growing whilst the Danish population is falling. This is because Denmark was more active installing turbines in the 1980s, whilst Germany has been more active in 1990s. Denmark is now replacing many smaller turbines with fewer, larger machines.

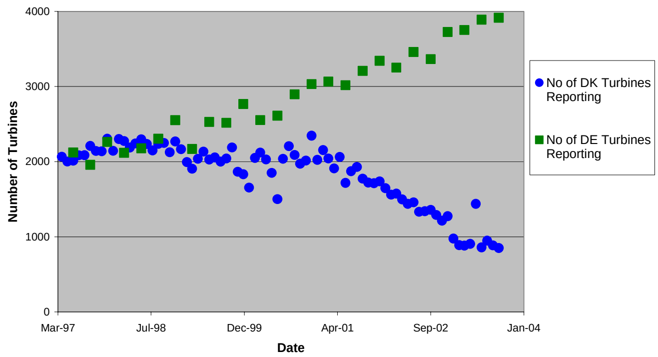

Figure 3, Variation in Number in two Populations.

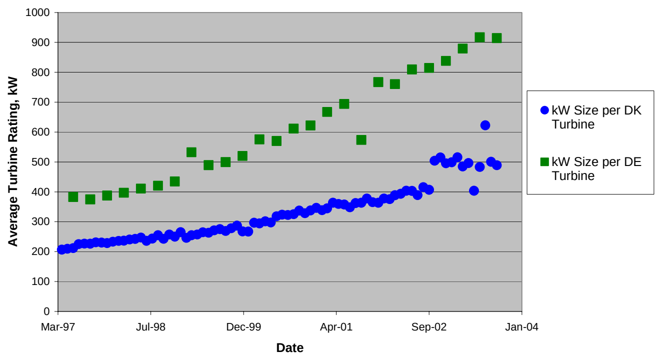

Figure 4, Variation in Average Turbine Rating in two Populations.

Figure 4 confirms this, because the average rating of a German turbine is larger than a Danish turbine. This is significant because a turbine < 1000 kW will be of the fixed speed induction generator type, whereas >= 1000 kW will be variable speed with an electrical converter, making it more complex and perhaps more prone to failure.

In this paper we want to use the average Failure Rate to select a life model, even though the technology, configuration, size and number of wind turbines in the survey vary with time. We could consider the variations in average Failure Rate as noise distorting the true average value. To take this approach answers are needed to the following questions:

- Is there a statistical model to describe the average failure rate of the turbines surveyed in this paper?
- What is the effect of the large, new turbines being installed, on the historic data?
- Is the reliability of large, new turbines improving?

5. Probability Model

The 7 years of data obtained from Windstats has a variable Population at each interval, a month for Danish and a quarter for Germany data. The data has been reorganised so that Populations and Failure Rates are available for 28 quarters for both Danish & German data, as statistical analysis shows that there is no loss of information after reorganisation. It is necessary to consider a group of turbines in a given quarter, as an independent Population, which varies in each subsequent quarter. If it is assumed that the times between failures are Independently & Identically Distributed (IID) exponential random variables [5] then the HPP model [6] describes the probability, P, of having N failures through time t, as:

$$P(N(t)=n)=\frac{1}{n!}(\lambda t)^n e^{(-\lambda t)}, \quad n=0,1,2.... \qquad (4)$$

Where the Failure Rate, λ, is the intensity function of the Poisson Process and the probability, P, that the n^{th} failure will occur before time t is defined by:

$$P=\int_0^t \frac{t^{n-1}}{(1/\lambda)^n \Gamma(n)} e^{(-t/(1/\lambda))} dt \qquad (5)$$

Considering the turbines in each population at k quarters as k independent Populations, the failure process is an HPP with Failure Rate intensity $\lambda=1/\theta$ and MTBF, θ, constant for each quarter. This assumption is reasonable from the engineering point of view, because:

- Wind turbines are renewed and have similar Subassemblies, even though the Populations vary from quarter to quarter.
- Figures 4 shows that Danish turbines are smaller while Figure 3 suggest that they are older and can be assumed to have survived beyond Early Failures into Constant Failure Rate, making the HPP model appropriate to them.
- The varying Population has no effect on the analysis, if we take the average failure number of all the turbines reported in quarter to be the failure number of a single turbine.

To evaluate the reliability of wind turbine and its Subassemblies, the probability of observing n or more failures in the interval $[t_1\ t_2]$ will be calculated:

$$\begin{aligned} P(N\geq n) &= \sum_n^{\infty} P(N=n) \\ &\equiv \sum_n^{\infty} \frac{1}{n!}(\lambda(t_2-t_1))^n e^{-\lambda(t_2-t_1)} \qquad (6) \\ &\equiv 1-P(N\leq(n-1)) = 1-\sum_0^{n-1}\frac{1}{n!}(\lambda(t_2-t_1))^n e^{-\lambda(t_2-t_1)} \end{aligned}$$

Since the data from Windstats is processed by analysing k identical repairable subassembly Populations, it is necessary next to test whether all k subassembly Populations have the same parameter θ.

6. Variation in MTBF between Quarters for each Subassembly

For all k Subassemblies to have the same MTBF, θ, the following hypothesis needs to be satisfied:

$H_0: \theta_1=\theta_2=....=\theta_k$ versus $H_1: \theta_1\neq\theta_2\neq....\neq\theta_k$.

The hypothesis-testing procedure is based on the Likelihood Ratio principle and the use of the chi-square approximation of the test statistic [7]. The likelihood ratio LR is:

$$LR = \frac{max_{H_{0\,ture}} L(\theta_1,\theta_2,...,\theta_K)}{max\, L(\theta_1,\theta_2,...,\theta_K)}$$

$$= \frac{max_{\theta}\, \theta^{-\Sigma_{i=1}^{k} n_i} exp(-\sum_{i=1}^{k} T_i/\theta)}{max_{\theta_1,\theta_2,...,\theta_k} \prod_{i=1}^{k} \theta_i^{-n_i} exp(-T_i/\theta_i)} \qquad (7)$$

$$= \frac{\hat{\theta}^{-\Sigma_{i=1}^{k} n_i} exp(-\sum_{i=1}^{k} T_i/\hat{\theta})}{\prod_{i=1}^{k} \tilde{\theta}_i^{-n_i} exp(-T_i/\tilde{\theta}_i)}$$

The numerator in Equation 7 indicates the Likelihood Function from all k identical Populations. The denominator in equation is the product of k Likelihood functions for k Populations.

The Likelihood Ratio statistic

$$-2\log LR = -2(\sum_{i=1}^{k} n_i)\log\hat{\theta} - 2\sum_{i=1}^{k} n_i \log\tilde{\theta}_i \qquad (8)$$

is distributed approximately as a chi-square with k-1 degrees of freedom. Let $\chi_0^2=-2\log_e LR$. Giving a specified value α, we have $\chi_{\alpha,(k-1)}^2$ as the percentage point. The test procedure calls for rejecting the null hypothesis H_0 when the value of this ratio χ_0^2 is large, say, whenever $\chi_0^2 > \chi_{\alpha,(k-1)}^2$. In other words a large value of $-2\log_e LR$ leads to a rejection of the null hypothesis. If null hypothesis is not rejected, the θs are equal and the Populations are identical in the sense that their MTBFs are the same.

For a test with α=0.05, we would reject the null hypothesis when $-2\log_e LR > \chi_{\alpha,(k-1)}^2 = 18.3$.

For a test with α=0.10, we would reject the null hypothesis when $-2\log_e LR > \chi_{\alpha,(k-1)}^2 = 16.0$.

Table III is an example of the calculated results of the Likelihood Ratio statistic with size α=0.05 from Danish data. It shows that the Subassemblies in each quarter have the same MTBF. Similar results were obtained for the German data. Next we will estimate the MTBFs of all type of Subassemblies.

7. Comparison between Subassembly Failure Rates in National Populations

This section considers the variability of Subassembly reliability between the Danish & German data. The observed data for the time to failure in each subassembly are of the form:

$$0 < t_{11} < t_{12} < ... < t_{1n_1} < T_1$$

$$0 < t_{21} < t_{22} < ... < t_{2n_2} < T_2$$

.

.

$$0 < t_{k1} < t_{k2} < ... < t_{kn_k} < T_k$$

Danish Data			
Subassemblies	**$-2\log_e$LR**	**Null hypothesis**	**Conclusion**
Main Shaft	0.0017	Accepted	Identical
Gearbox	0.0025	Accepted	Identical
Mechanical Brake	0.0036	Accepted	Identical
Generator	0.0064	Accepted	Identical
Hydraulic System	0.0016	Accepted	Identical
Yaw System	0.0041	Accepted	Identical
Electrical Control	0.0012	Accepted	Identical
Air brakes	0.0024	Accepted	Identical
Coupling	0.0021	Accepted	Identical

Table III, Summary of results of Likelihood Ratio test.

where t_{ij} denote the time to the j^{th} Failure from the i^{th} quarter. Suppose that n_i failures are observed for i^{th} quarter. We define T_i to be the time that data collection ceased for i^{th} quarter. There are 28 quarters, so $k=28$. Both Danish and German data have 12 Subassemblies, such as Shaft, Gearbox And Generator, so that we will have 12 Subassembly MTBFs, θ_k.

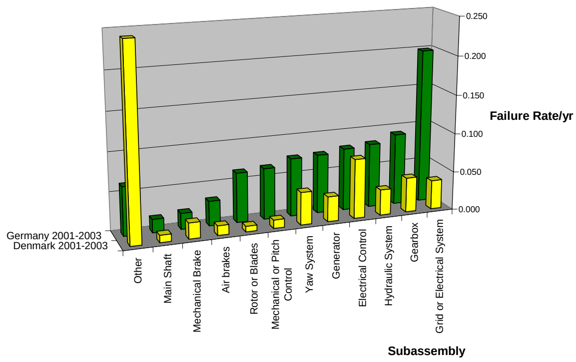

Figure 5, Variation in Subassembly Failure Rates for the two Populations in the Overall Period.

Figure 5 shows the Failure Rate for each Subassembly in the two National Populations over the period 2001-3, when the technology of the two Populations is closest. Comparing the Failure Rates of Subassemblies between Denmark and Germany, it can be seen that, while Danish Failure Rates are lower, for some Subassemblies the two populations have similar Failure Rates on, for example, the Main Shaft, Mechanical Brake and Electrical Control. This implies that Danish and German turbines could have similar reliability models, using the HPP model. Not surprisingly, since Brakes, Shafts and Control Systems produced in varying sizes for the same industry are likely to have similar Failure Rates in different Populations.

To quantify the uncertainty due to 'sampling error', we choose 95% confidence interval to express the precision of estimation. Assuming that all Populations are failure-truncated, we have the Confidence Interval, $\theta_{\alpha/2}$, for θ of:

$$\theta_{\alpha/2} = \frac{2\sum_{i=1}^{k} T_{i,n_i}}{\chi^2_{\alpha/2}\left(2\sum_{i=1}^{k} n_i\right)} < \theta < \frac{2\sum_{i=1}^{k} T_{i,n_i}}{\chi^2_{1-\alpha/2}\left(2\sum_{i=1}^{k} n_i\right)} = \theta_{1-\alpha/2} \qquad (9)$$

Under this assumption, the Confidence Interval is narrower if some of the Populations are time-truncated, because more information is included if they are. Using Failure Rate data to calculate the Confidence Interval and taking the average as the Confidence Interval for each Subassembly, i.e. multiplying the confidence intervals of the original data by the number of turbines reported. When $(2\Sigma n_i)>45$, we can use the approximate formula:

$$\chi^2_{\alpha}\left(2\sum_{i=1}^{k} n_i\right) \approx 2\sum_{i=1}^{k} n_i + \sqrt{2\times 2\sum_{i=1}^{k} n_i}\, z_a \qquad (10)$$

Where Z_a is the Z-value associated with right-hand tail area of α for a standard normal distribution.

Using Equation 9, we obtain the results of the analysis giving a high confidence in the Failure Rate data for the Danish and German populations.

8. Probability of Failures in a Wind Turbine

As stated in the introduction, the HPP model describes the probability of certain events. In this section we will give the probability of observing failures in a certain period. Following Equations 4 & 6 probabilities have been computed to indicate the probability of observing, in periods of 1 and 25 years, the following number of failures:

- no failures, $P(N_2 = 0)$,
- 1 or more failures $P(N_2 \geq 1)$,
- 2 or more failures $P(N_2 \geq 2)$.

Results are shown in Figure 6 for Danish turbines only, which show a reasonable probability of 25 years life with very few failures. Results for German turbines are not displayed but show that they deteriorate more rapidly than the Danish turbines on the basis of this model.

9. Discussion

The HPP model will give a constant Failure Rate with time for turbines in a National Population. However, Figure 1 shows a decreasing Failure Rate against time for both National Populations. In the case of the Danish Population the rate of decrease in Failure Rate is slower and the HPP model is a reasonable assumption. This decrease could be due to the improving reliability of long-serving, reliable, turbine designs.

Yet the German data, with greater numbers of large turbines of new technology, as shown in Figures 3 & 4, exhibits a greater decrease in Failure Rate with time than the Danish data.

When new turbines are put into operation Failure Rates will increase due to Early Failures. Furthermore, large turbines of new technology and greater complexity should be more prone

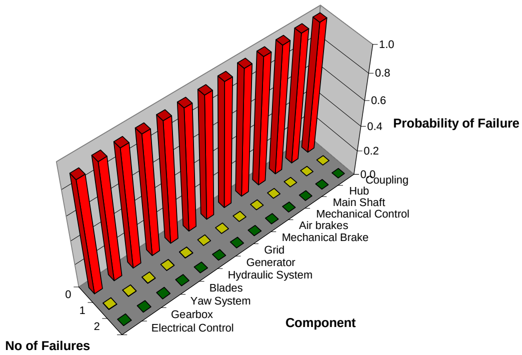

Figure 6a, Probability of numbers of failures in 1 year for Danish Turbines

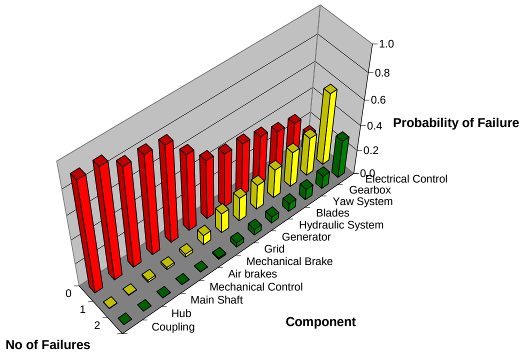

Figure 6b, Probability of numbers of failures in 25 years for Danish Turbines

to failure, increasing the Failure Rate still further. However, when turbines move out of Early Failure, the Failure Rate of the population should fall. This could be what is happening to the German data. One could conclude that the large turbines of new technology and greater complexity are actually more reliable than the older, smaller, Danish turbines and this may be the cause of the decreasing German Failure Rate.

The HPP model has demonstrated the reliability pattern of the Danish Population. But, only the PLP model can be used to model the failure pattern of the German Population, with equipment improving so markedly in time. When $\beta < 1$, the failure intensity, λ, in the PLP model of Equation 2, decreases with time, t, and the times between consecutive failures become longer, as shown in Figures 1 & 2.

Figure 5 has shown the comparative Failure Rates of key Subassemblies in the turbines. This shows that Electrical Controls, Electrical Systems and Gearboxes have significant Failure Rates compared to other Subassemblies, particularly in the German population. This indicates that an improvement of design is desirable. It has been suggested that reliability could be raised and cost reduced by eliminating gearboxes, but, Figure 5 does not show gearboxes as the least reliable part of a wind turbine. Large direct drive turbine products, without gearboxes, are available in the market. However, to retain the variable speed capability a direct drive, low speed generator and fully-rated converter are substituted for the gearbox. Direct drive generators are heavy and costly at sizes >2MW. Fully-rated converters expand the Electrical Control & System Subassemblies which presently cause the highest Failure Rates. Such a combination, of direct drive, low speed generator and fully-rated converter could have a negative overall effect on the cost, weight and reliability of a turbine. On the other hand such a change could improve the fault withstand capability of the turbine on the network.

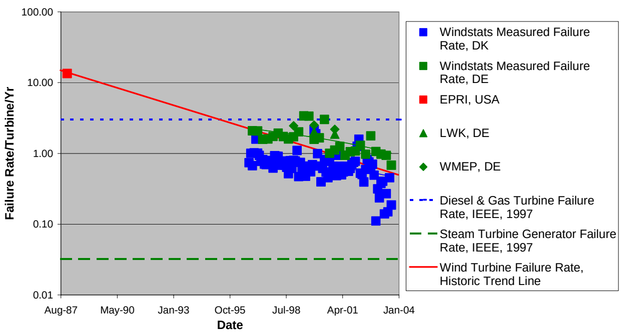

Figure 6, Average Failure Rates of German and Danish Wind Turbines in historical context and compared to the Failure Rates of other Power Sources.

In Figure 6 the results of other reliability surveys in Germany, taken from [3], confirm the trend shown in this paper of the Windstats data for German turbines, increasing confidence in the results shown. Results from the USA in the 1980s, also quoted in [3], show how much wind turbine reliability has improved over the past 16 years, placing the trends shown in this paper in context. Figure 6 also shows the Failure Rates for diesel, gas and steam turbine generation, reported by the IEEE in [9] & [10]. The striking observation here is that wind turbines are now achieving better reliability than diesel generation and have a trend where they could achieve similar reliability to steam turbine generation in relatively few years.

10. Conclusions

A number of general conclusions about wind turbine reliability can be drawn from this survey:

- There is a downward trend in Failure Rate in both German & Danish wind turbine populations
- Statistical analysis of German and Danish Failure Rate data shows that the populations at each data interval are independent but can be considered to be identical for the purposes of modelling their MTBFs.
- The HPP model for Turbine Life has been demonstrated to be applicable for Danish Turbines because of the increasing age of their long-serving, reliable, turbine designs, which lie in the Constant Failure Rate region of the Life Curve.
- The PLP model for Turbine Life needs to be used for German Turbines because they have lower average age and are in the Early Failures region of the Life Curve.
- The introduction of larger turbines with more technological complexity in Germany is raising their average Failure Rate but the trend in Failure Rate is downward at a faster rate than in the Danish population. This suggests that the newer turbines are potentially as reliable as their smaller predecessors, despite their increased complexity. This can only be proved mathematically by further work on a PLP model.
- The Failure Rates of Subassemblies in the wind turbines from both German & Danish populations show some similarities suggesting that a generic model of wind turbine reliability is possible.
- The analysis shows that the highest subassembly Failure Rates occur in Electrical Controls & Electrical Systems. Gearboxes have a significant Failure Rate in both National Populations.
- The analysis of subassembly Failure Rates has enabled the statistical prediction of time to failure of key components, showing that turbines based on the Danish data have very few failures in 25 years. The results for German turbines show a lower life expectancy.
- Wind turbines in Germany & Denmark now have a better reliability than diesel generating sets and are approaching the reliability of steam turbine generating sources.
- There appears to be a periodicity in Failure Rates of Danish wind turbines, which the authors tentatively ascribe to weather effects.

Acknowledgements

The authors would like to thank AMEC Wind Energy, Hexham, for encouragement and information.

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